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6. AUTHOR(S)
PROFESSOR LEE

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
BOSTON UNIVERSITY
DEPT OF ELECTRICAL & COMPUTER SYSTEMS ENG.
BOSTON, MA 02215

8. PERFORMING ORGANIZATION
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Research on source mechanisms and radio effects of ionospheric plasma disturbances had been conducted, including theories, field experiments at Arecibo, Puerto Rico, and laboratory experiments with the Versatile Toroidal Facility (VTF) at MIT Plasma Fusion Center. Several graduate students and undergraduate students participated in the research projects and completed their thesis work under the supervision of Prof. Min-Chang Lee.

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Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139-4294
Telephone: 617/253-8100

To: Dr. Jim Kroll, Program Manager, AFOSR
From: Prof. Min-Chang Lee MCL
Date: August 19, 1994
Re: Progress Report on Sponsored Research Programs titled "Source Mechanism and Radio Effects of Ionospheric Plasma Disturbances" (AFOSR-92-0001) ~~and "Studies of Enhanced Radar Backscatter" (F49620-92-J-0297)~~

Final Report on

"Source Mechanisms and Radio Effects of Ionospheric Plasma Disturbances"

Grants number AFOSR-92-0001

For the Period of October 1, 1991 - September 30, 1994

Research on source mechanisms and radio effects of ionospheric plasma disturbances has been conducted, including theories, field experiments at Arecibo, Puerto Rico, and laboratory experiments with the Versatile Toroidal Facility (VTF) at MIT Plasma Fusion Center. Several graduate students and undergraduate students participated in the research projects and completed their thesis work under the supervision of Prof. Min-Chang Lee. Major research results are briefly summarized as follows.

A source mechanism has been proposed to explain the observation of a low- frequency ($\sim$ 500 Hz) mode in conjunction with symmetric sidebands, displaced by approximately 500 Hz off the carrier frequency of an injected VLF wave from a ground-based transmitter. Our theoretical analysis shows that the injected VLF wave parametrically excites a purely growing mode and both the Stokes and the anti-Stokes sidebands of the lower hybrid waves. The Doppler shifted frequencies of these modes resulting from the satellite motion adequately account for both the sidebands and the low frequency mode observed in the experiments.

Reflection of radio waves from turbulent plasma layers was investigated with potential

A-1

applications to radio communications and space surveillance. In addition to theoretical analyses of the problem, simulation experiments with lightning-induced plasmas were conducted on campus with the MIT S-band, C-band, and the Millstone UHF radars. This lightning induced plasma model is applied to the problem of radio wave reflection from an artificially produced plasma patch in the atmosphere. Both the monostatic (backscatter) and bistatic (specular) geometries are analyzed for diagnosing the structure of plasma turbulence and for radio communication purposes.

We have carried out ionospheric heating experiments at Arecibo, using both vertically and obliquely injected HF waves to study the spectral characteristics of the HF enhanced Langmuir waves. During the vertical heating experiments, the cascading spectra of Langmuir waves due to the PDI (parametric decay instability) were constantly observed. Occasionally seen was a relatively weak and narrow band of Langmuir waves whose frequencies are greater than the HF heater frequency by tens of kHz known as free modes or anti-Stokes modes in the literature. The observation of these frequency upshifted Langmuir waves is explained by a nonlinear scattering process, whereby the source Langmuir waves generated by PDI along the geomagnetic field are scattered off the density fluctuations associated with the existing lower hybrid waves. These lower hybrid waves can be generated by lightning-induced VLF (whistler) waves via parametric instabilities or a scattering process.

Large enhancements of the incoherent radar backscatter echoes around 90 km were frequently seen at Arecibo during our heating experiments. Our statistical study of these enhanced radar backscatter (ERB) events over the past two years at Arecibo has indicated that they are plasma layers possibly caused by meteors or HF wave triggered particle precipitation. Auto-correlation function (ACF) measurements of radar echoes, can further distinguish one from the other. Our preliminary data analysis and theoretical consideration suggest tentatively a scenario of the VLF (whistler) wave triggered particle precipitation at Arecibo as follows. Arecibo, Puerto Rico is located near the footprint of the geomagnetic flux tube at L = 1.47. Kilometer (and larger)-scale field aligned waveguides can be generated by the Arecibo HF heating facility, guiding favoravly VLF (whistler) waves from the lower ionosphere into the radiation belts. The VLF (whistler) waves can be those produced by lightning or injected from a nearby naval transmitter operated at 28.5 KHz. Whistler wave-particle interactions in the radiation belts can potentially lead to particle precipitation, causing anomalous ionization in the lower ionosphere.

Laboratory experiments with the Versatile Toroidal Facility (VTF) have also been actively performed to investigate plasma turbulence and effects on electromagnetic waves. These experiments are aimed at simulating the ionospheric plasma environment and cross-checking our ionospheric heating experiments at Arecibo, Puerto Rico. The Versatile Toroidal Facility (VTF) is a large plasma device constructed by over 25 graduate and undergraduate students of Min-Chang Lee at MIT Plasma Fusion Center. VTF can generate magnetized plasmas with sharp density gradients and intense magnetic field-aligned currents. The VTF plasma thus have the key characteristics of the ionospheric plasmas, especially in the auroral region. The VTF plasma turbulence is structured with low-frequency wave modes which can be similarly produced by the sharp density gradients and/or field-aligned currents in the ionospheric F region and in the topside ionosphere. VTF can adequately simulate the naturally occurring plasma turbulence in the auroral ionosphere and complement field experiments in the ionospheric plasmas.

The outcome of the afore-mentioned research work leads to the publication ten (10) journal articles and nine (9) proceedings papers. Three (3) graduate theses and three (3) undergraduate thesis have been completed. The paper entitled "Radar studies of lightning induced plasmas with potential applications to radio communications and space surveillance" by Y.R. Dalkir and M.C. Lee won the 1st position in the 1993 URSI Student Prize Paper Contest held at the National Radio Science Meeting, Boulder, Colorado, January 5-8, 1993.

(A) Journal Articles:

(1) "A source mechanism producing HF-induced plasma lines (HFPLs) with upshifted frequencies" by S.P. Kuo and M.C. Lee, **Geophysical Research Letters**, *19*, 249, 1992.

(2) "A mechanism responsible for the observation of symmetric lower hybrid sidebands and a low frequency mode in the upper ionosphere" by Y.R. Dalkir, M.C. Lee, K.M. Groves, and S.P. Kuo", **Journal of Geophysical Research**, *97*, 17195, 1992.

(3) "Analysis of coupled hydromagnetic wave equations with a finite difference scheme", by M.H. Whang, S.P. Kuo, and M.C. Lee, **Journal of Scientific Computing", 7**, 241, 1992.

(4) "An experimental study of OTH radar using Bragg reflection from artificial ionizing layers of gas", by S.P. Kuo, Y.S. Zhang, M.C. Lee, P.A. Kossey, and R.J. Barker, **Radio Science**, *27*, 851, 1992.

(5) "The role of nonlinear beating currents in the theory of parametric instabilities" by S.P. Kuo, M.C. Lee and J.A. Fejer, **Journal of Geophysical Research**, *98*, 9515, 1993.

(6) "On the altitude of HF-enhanced plasma lines (HFPLs)" by S.P. Kuo, J. Huang and M.C. Lee, **Journal of Geophysical Research**, *98*, 1,671, 1993.

(7) "Generation of ELF and VLF waves by HF heater-modulated polar electrojet via a thermal instability process", **Geophysical Research Letters**, *20*, 189, 1993.

(8) "Radar studies of lightning-induced plasmas with potential applications to radio communications and space surveillance" by Y.R. Dalkir and M.C. Lee, **Radio Science**, *28*, 1039, 1993.

(9) "Thermal instability excited in the electron resonance heating of plasmas", by S.P. Kuo and M.C. Lee, **Journal of Plasma Physics**, *49*, 515, 1993.

(10) "Analysis of EM wave scattering by ionospheric irregularities", by A.Y. Ho, S.P. kuo, and M.C. Lee, **Radio Science**, *29*, 1131, 1994.

(B) Proceedings Papers

(1) "Nonlinear ionospheric propagation effects of UHF radio signals" by K.M. Groves, M.C. Lee, and J.C. Foster, in **Physics of Space Plasmas** , Scientific Publishers, Cambridge, MA, No. 11, 377, 1992.

(2) "Satellite measurements of symmetric lower hybrid sidebands and a low frequency mode during VLF wave injection", by Y.R. Dalkir, M.C. Lee, K.M. Groves, and S.P. Kuo, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 239, Cambridge, MA, 1993.

(3) "Frequency-upshifted Langmuir waves produced by RF heating of ionospheric plasmas" by M.C. Lee, Y.R. Dalkir, K.M. Groves, S.P. Kuo, M.P. Sulzer, and K.D. Vilece, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 248, Cambridge, MA, 1993.

(4) "Generation of artificial ionospheric ducts for guided VLF wave propagation" by M.C. Lee, S. Basu, K.M. Groves, K.L. Koh, M.P. Sulzer and K.D. Vilece, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 252, Cambridge, MA,

1993.

(5) "Ionospheric heating experiments at Arecibo using two HF heaters" by S.P. Kuo, M.C. Lee, Y.R. Dalkir, K.M. Groves, K.L. Koh, K.D. Vilece and M.P. Sulzer, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 256, Cambridge, MA, 1993.

(6) "Electron cyclotron range of frequencies propagation in critically dense cold magnetoplasmas", by D.T. Moriarty, R.R. Parker, and M.C. Lee, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 260, Cambridge, MA, 1993.

(7) "Analysis of electromagnetic wave scattering within a two-dimensional plasma density irregularity in the ionosphere" by A.Y. Ho, S.P. Kuo, and M.C. Lee, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 280, Cambridge, MA, 1993.

(8) "Scintillation effects on incoherent scatter radar observations of enhanced ion acoustic waves" by K.M. Groves, M.C. Lee, J.C. Foster, and F.T. Djuth, **Proceedings of 1992 International Beacon Satellite Symposium**, pp. 284, Cambridge, MA, 1993.

(9) "On the spectral characteristics of the Langmuir mode waves produced by RF heating of ionospheric plasmas" by M.C. Lee, Y.R. Dalkir, D.T. Moriarty, K.D. Vilece, K.M. Groves, M.P. Sulzer and S.P. Kuo, **Physics of Space Plasmas**, Scientific Publishers, Cambridge, MA, No. 12, 427, 1993.

(C) Graduate Theses:

(1) K.D. Vilece, "Experimental study of anti-Stokes Langmuir modes and particle precipitation produced by RF heating of ionospheric plasmas", M.S. Thesis, Department of Nuclear Engineering, **M.I.T.**, May, 1992.

(2) D.T. Moriarty, "Electron cyclotron range of frequencies propagation in critically dense cold magnetoplasmas", M.S. Thesis, Department of Nuclear Engineering, **M.I.T.**, September 1992.

(3) Y.R. Dalkir, "Radio wave interactions with plasmas in the atmosphere", M.S. Thesis, Department of Electrical Engineering and Computer Science, **M.I.T.**, May, 1993.

(D) Undergraduate Thesis:

(1) M.J. Starks, "Artificial communication paths: table-top demonstration and experiments at Arecibo", B.S. Thesis, Department of Electrical, Computer, and Systems Engineering, **B.U.**, May, 1993.

(2) M.F. Mastromonaco, "Current-driven processes in a magnetized plasmas: theory and laboratory experiments", B.S. Thesis, Department of Electrical, Computer, and Systems Engineering, **B.U.**, May, 1994.

(3) S.M. Murphy, "Characterizing low frequency wave behaviour inside the VTF", B.S. Thesis, Department of Electrical Engineering and Computer Science, **M.I.T.**, May, 1994.